STUDY NOTES

Green Chemistry BG 5th Sem KU (Batch 2016)

1. Green Chemistry

- ✓ The design of processes that reduce or eliminate the use and production of toxic products is known as green chemistry.
- ✓ The term was first used by Paul T. Anastas in the last decade of the 20^{th} century
- ✓ Green Chemistry implies:
    - Prevention of pollution rather than treatment of pollution
    - Environmentally Benign Chemistry
    - Sustainable Chemistry
    - Ecofriendly Chemistry
    - Clean Chemistry
- ✓ Green chemistry should not be confused with environmental chemistry as environmental chemistry deals with various facets of pollution, degree of pollution and treatment of pollution, while as green chemistry does not lead to pollution at all, hence we say it prevents pollution.
- ✓ Thus green chemistry approach is a prevention approach, while as environmental chemistry approach is a treatment approach. Since prevention is better than cure, we may say green chemistry is better than environmental chemistry.
- ✓ To develop a perfectly green chemical pathway is not easy. However green chemists try their best to maximize the greenness in any process as far as possible.
- ✓ Green chemistry is generally aimed at
    - Producing chemicals which are safe for biotic as well as abiotic environment.
    - Using cost and energy effective methods and procedures.

- Designing processes that reduce or eliminate the use and production of toxic materials
- Minimizing the production of wastes.
- Avoiding the production of non-biodegradable materials/products.
- Maximizing the use of raw-materials from renewable resources

✓ As per the father of Green Chemistry, Paul T. Anastas, green chemistry utilizes a set of 12 principles that aim to achieve and increase the greenness in a process.

2. Principles of Green Chemistry

✓ The twelve principles of green chemistry that have been formulated (Ref. **P.T. *Anastas and J.C. Warner 'Green Chemistry Theory and Practice', Oxford University Press, New York, 1998***) are listed below:

1. Prevention
2. Atom Economy
3. Less Hazardous Chemical Synthesis
4. Designing Safer Chemicals
5. Safer Solvents and Auxiliaries
6. Design for Energy Efficiency
7. Use of Renewable Feedstocks
8. Reduce Derivatives
9. Catalysis
10. Design for Degradation
11. Real-time Analysis for Pollution Prevention
12. Inherently Safer Chemistry for Accident Prevention

1. **Prevention: It is better to prevent formation of wastes than to treat the waste after it is formed.**

In designing a process/synthesis, the acronym, "Prevention is better than cure" must be obeyed. A chemical process/reaction must be carried out in such a manner so as to reduce/minimize or completely eliminate the production of wastes. Waste prevention is necessary because of the following reasons:-

(a) If a process produces waste, it invokes the need for its treatment/disposal, which in turn amounts to additional expenditure.

(b) Secondly if the waste is toxic or hazardous, the release of waste in to the environment leads to its pollution, which further invokes the need of treatment, causing additional expenses.

So we must try to devise processes/reactions that minimize the production of wastes to the best possible extent.

Since majority of the reactions produce the byproducts in addition to the normal desired product, we may say the byproducts of reactions are wastes.

A measure of waste known as E-factor has been described by R. A. Sheldon who defined it as the ratio of the mass of waste (kg) to the mass of desired products (kg) [*Ref. Sheldon, R.A.(2007). "The E Factor: Fifteen years on". Green Chemistry. 9 (12):1273]*.

E-factor, also known as Environmental (Mass) efficiency factor is calculated as:

E-factor = Total Waste (kg) / Product (kg)

As per Sheldon, E-factor calculated for various industries is depicted below in a tabulated form as:

Type of Industry	Annual production (t)	E-factor	Total Waste (t, approx
Oil refining	10^6 - 10^8	**ca. 0.1**	10^6
Bulk Chemicals	10^4 - 10^6	**< 1-5**	10^5
Fine Chemicals	10^2 - 10^4	**5->50**	10^4
Pharmaceuticals	10^0 - 10^2	**25->100**	10^3

*The data has been taken from ***R. A. Sheldon, Chem. & Ind. 1 December 1992, p. 904***.

- **Assignment 1: Work out any two reactions in organic chemistry that produce wastes?**

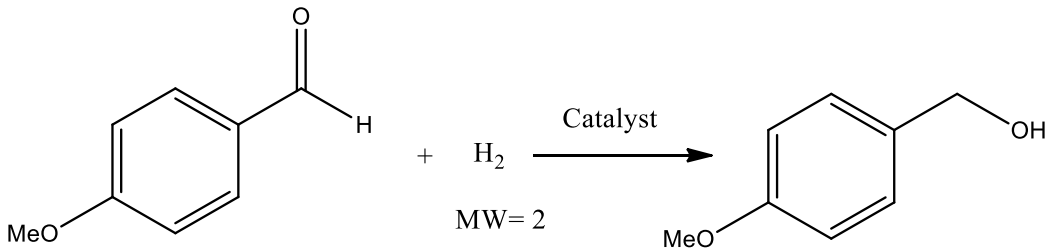
2. **Atom Economy: Synthetic methods should be designed to maximize the incorporation of raw material used in to the products.**

- ✓ It is one of the fundamental and most important principle of green chemistry.
- ✓ The concept of atom economy has been developed by B.M. Trost.
- ✓ Atom economy is defined as the measure of the amount of reactants that end up directly into the desired product
- ✓ It is often referred to as percent atom utilization.
- ✓ R. A. Sheldon has also developed the same concept given as:

$$\%\ Atom\ Economy = \frac{Formula\ weight\ of\ atoms\ utilised\ in\ the\ desired\ products}{Formula\ weight\ of\ reactants\ used\ in\ the\ reaction} \text{ x } 100$$

$$\%\ Atom\ Economy = \frac{Relative\ molecular\ mass\ of\ desired\ product}{Relative\ molecular\ mass\ of\ all\ reactants} \text{ x } 100$$

e.g the percent atom economy of the reaction given below is as:



MW= 136 MW= 2 MW= 138

$$\% \, \boldsymbol{Atom\ Economy} = \frac{\mathbf{138}}{\mathbf{136+2}} \text{ x } 100 = 100 \text{ percent}$$

- **Assignment 2: Calculate the atom economy of any two organic reactions of your choice?**

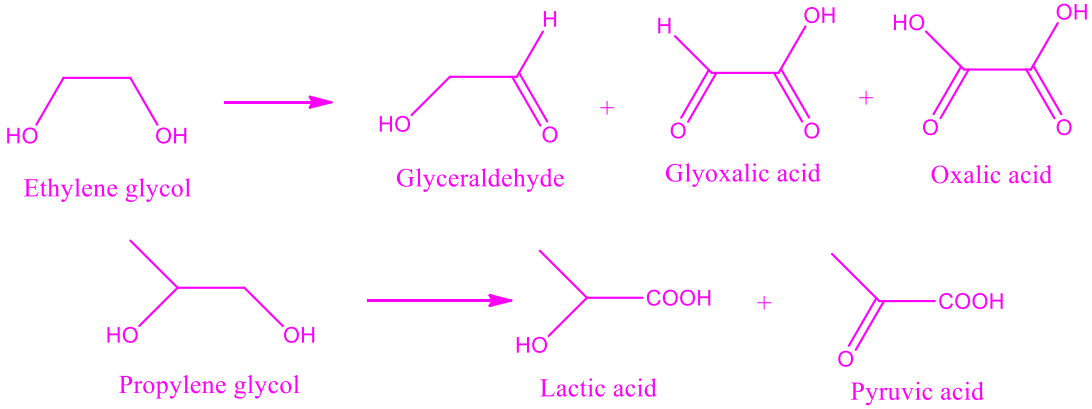
3. **Less Hazardous Chemical Synthesis: Wherever practicable, synthetic methods should be designed to use and generate less toxic or non-toxic substances.**

   This principle aims at the reduction of hazard associated with the chemical entities that form the product in a chemical synthesis. Traditionally chemists use any chemical entity whenever required. Green approach removes the need of use of everything and prefers safer chemical entities or reagents. Ideally the use and production of toxic substances, is avoided, when safer alternatives are available. Further production of toxic wastes in synthesis can be problematic, which further demands safe disposal. These wastes or main products, if toxic may harm the workers, who need to be protected which in turn adds to the cost of pollution. An important example concerning the use of safe chemicals is the manufacture of polystyrene foam sheet packaging material, wherein chemists have replaced the use of hazardous chlofluorocarbons (which cause ozone depletion, global warming) by CO_2 as the blooming agent.

4. **Designing safer chemicals:- Products should be designed to preserve their efficacy of function while reducing toxicity**

   Chemical products to be synthesized should be safe to use. Thalidoimide presents an example of a typically unsafe drug, used for reducing the nausea and vomiting in pregnant women. The children born to such women suffered birth defects, which necessatiated the ban on the use of this drug. Manipulation of molecular structures has helped in lot in the

design of safer chemicals. A well-known example of retrometabolic design is that of ethylene glycol, which is used as an antifreeze and has been replaced by propylene glycol which is less hazardous. Ethylene glycol once ingested in to body gets converted in to glyceraldehyde, glyoxylic acid and oxalic acid which are toxic to body, as against propylene glycol which gets metabolized into normal body metabolites like lactic and pyruvic acid. The lethal dose of ethylene glycol for man is 1.4 ml/kg while as the lethal dose of propylene glycol for man is 7 ml/kg. Thus in the design of safer chemicals propylene glycol is used as an antifreeze. [Ref:-Introduction to Green Chemistry 2nd Edition, A. Matlack, CRC Press, Taylor and Francis].



5. <u>Safer Solvents and auxillaries: The use of auxillary substances (solvents, separation agents) should be made unnecessary whenever possible and innocuous when used.</u>

Chemists generally use any organic solvent of their choice in synthetic reactions. Most often these solvents are the volatile organic solvents (VOCs) and have a major environmental concern, as they are able to form low-level ozone and smog through free-radicals air oxidation processes. They are also highly flammable and cause adverse effects like eye-irritation, headaches and allergic skin reactions in human biengs. These facts have made it necessary to use green alternative solvents. However if possible the use of solvents should be avoided. If however there is no choice and use of solvent becomes imperative, it is recommended to use such solvents which are inert, have low

toxicity, easy to recycle without contaminating the products. The solvent selected should not have any negative impact on the environment or human health. e.g. halogenated solvents like $CHCl_3$, CCl_4 are suspected carcinogens and to avoid their use, green alternatives like water, ionic liquids, liquid CO_2 have been used.To avoid the problems associated with the conventional VOCs, immobilized solvents have been harnessed. Such solvents maintain the solvency, are non-volatile and do not pose any environmental problem.

6. Design for energy efficiency: Energy requirements of a reaction should be recognized for their environmental and economic impacts and should be minimized if possible. Wherever possible synthetic methods should be carried out at ambient temperature and pressure.

- ✓ Energy requirements for the chemical reactions must be as minimum as possible
- ✓ Most commonly used conventional energy source in reactions is the thermal energy.
- ✓ Thermal energy is non-specific, as it is not targeted directly at a bond or the molecules undergoing the reaction.
- ✓ Much of the thermal energy is wasted in heating up the reactors, solvents and even general environment.
- ✓ To avoid these things associated with thermal energy, alternate and more specific forms of energy are used.
- ✓ These sources are green energy sources include photochemical, microwave and ultrasonic sources of energy.
- ✓ This principle requires that energy consumption be minimized in the reactions.
- ✓ Various possible ways to improve the energy efficiency in processes include:
    a) Good insulation and well maintained equipments reduce heat and energy losses.

b) Generally such reactants should be chosen that require less energy/lower temperatures

c) It advocates that such catalysts be developed such that processes can be run at lower temperature an pressure thereby reducing the energy consumption.

7. Use of renewable feed stocks (Raw-materials): A raw material or feedstock should be renewable rather than depleting, whenever technically and economically practicable.

- ✓ Usually a starting material in a reaction or a process can be from a renewable or non-renewable source
- ✓ Green chemistry however demands that a particular starting material should always be from a renewable resource, so that it is made available in abundance and does not get depleted. e.g CO2, CH4, etc can be obtained from a natural sources and are available in abundance, and considered as renewable resources.
- ✓ This principle also implies the use of renewable energy technologies which include, solar energy, wind energy, biomass energy, biofuels, hydropower.
- ✓ Over the past few years, production of materials, chemicals, fuels has been done using renewable raw materials.. E.g Europe has successfully utilized rapeseed oil as raw material for the production of biodiseal. Another well-defined example is furnished by American company NatureWorks that uses bottles made from lactic acid polymers (PLA) made from lactic acid, obtained by the fermentation of dextrose obtained from starch, most commonly corn. It is believed that to produce one kg of PLA, 2.5 kg of corn is required [*Ref Rujnić-Sokele, M. (2007): Truths and mistakes about bioplastics. Polymers: Journal of Rubber and Plastics, Rubber and Plastics Corporation, Zagreb, 28_3: pp178-181. In Croatian*].

8. <u>Reduce derivatives: Unnecessary derivatization (blocking groups/ protection/ deprotection/temporary modification of a physical/chemical process should be avoided whenever possible.</u>

- ✓ Protecting groups in organic synthesis are important and used to protect a sensitive functionality from reaction reagents/conditions., which make the reaction go away in an unwanted direction, if unprotected.
- ✓ To understand this let us take an example below:

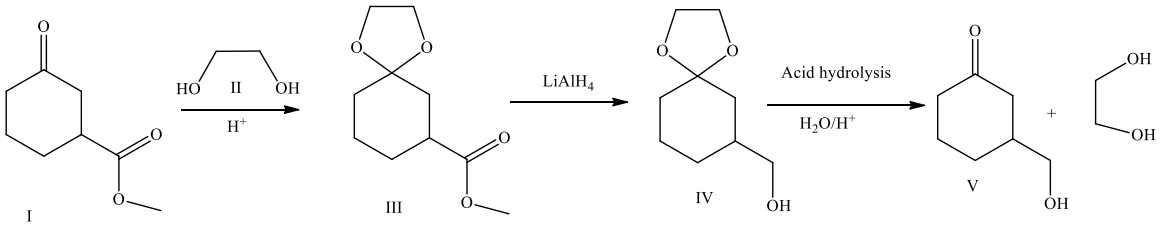
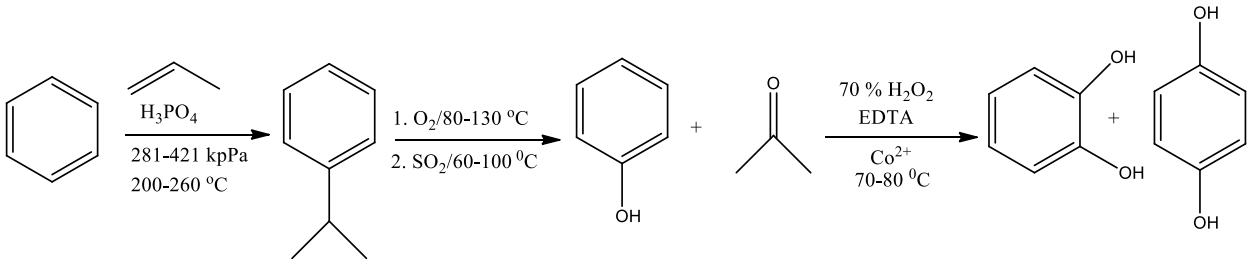


Figure 1: Protection/Deprotection of keto group.

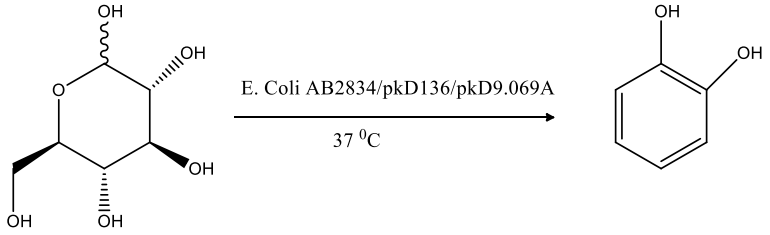
- ✓ In this example, in order to reduce the ester group in to alcohol group, the ketonic group needs to be protected. Protection is done by using ethylene glycol (II) to get the protected compound (III). The ester moiety in this protected compound can then be reduced by using $LiAlH_4$ to yield compound (IV). This compound (IV) can then be allowed to undergo acid hydrolysis, i.e. deprotection which yields the desired product with the generation of protecting group, ethylene glycol. Such type of protection and deprotection is too common in organic chemistry. In the above procedure, the protecting group is not incorporated in to the final product, which makes a reaction less atom economical. Thus as far as possible, the use of protecting groups should be avoided.

9. Catalysis: Catalytic reagents (as selective as possible) are superior to stoichiometric reagents

This principle advocates the use of catalytic reagents rather than the stoichiometric reagents. Being unchanged the catalytic reagent can be recovered completely as the reaction comes to an end. All catalysts including enzymes lower the activation energy of reaction, accelerating the reaction several million time, without being changed. Still biocatalysts stand out among all other catalysts because of their specificity in terms of stereochemistry, chemical selectivity. Compared to non-biological catalysts, biocatalysts have a great advantage given the rate of reaction, catalytic specificity, lower cost, etc., but lack of heat sensitivity and poor stability. Biocatalysts are biodegradable-catalysts, which imply less energy consumption. A classical example which demonstrates use of catalytic reagents is furnished by catechol. The classical catechol synthesis is derived from benzene, occurs in a number of steps and involves drastic reaction conditions giving rise to unwanted byproducts. However the biocatalytic route involves synthesis of catechol from glucose in just single step, involves the use of Escherchia coli and is economically viable, involving non formation of byproduct [Ref. *Anastas, P. T., Kirchhoff, M. M., Williamson, T. C. (2001): Catalysis as a foundational pillar of green chemistry. Appl Catal A: General, 221: 3-13]*.



Route A: Classical route to catechol, involves so many stoichiometric reagents, drastic conditions, biproduct formation



Route B: Biocatalytic route to catechol

Route A and Route B: [Ref:*Draths, K. M., Frost, J. W. in: Anastas, P. T., Williamson, T. C. (Eds.), Green Chemistry: Frontiers in Benign Chemical Syntheses and Processes, Ch. 9, Oxford University Press, New York, 1998, pp. 150–182*]

10. Design for degradation: Chemical products should be so designed that at the end of their function, they donot persist in the environment and break down in to innocuous degradation products

This principle demands the synthesis of such products, which after performing their function properly must be able to convert into non-toxic end-products. Generally we see a number of products being synthesized which do not degrade at the end of their usage. Thus it is required to produce a biodegradable product, otherwise it would remain/persist within the environment, may be taken up by plants/animals and as such gets accumulated with-in their biosystems, detrimental to the concerned species. As for example the organochlorine class of pesticides, e.g DDT is non-biodegradable and causes severe problem. Therefore a product be designed such that it degrades to innocuous products in the environment. It is now possible to place groups and other features within the molecules which will facilitate its degradation. Functional groups which are susceptible

to hydrolysis, photolysis or other possible changes have been used to ensure that products will be biodegradable.

11. **Real-time analysis for pollution prevention: Analytical technologies need to be further developed to allow for real time in process monitoring and control prior to the formation of toxic substances.**

Analytical technologies need to be developed that will allow the prevention and minimization of generation of hazardous wastes. One need to have accurate and reliable sensors, monitors, and techniques to assess the hazards that are present in the process stream. Using various techniques a process can be monitored for generation of hazardous byproducts and side reactions.

12. **Inherently safer chemistry for accident prevention: Substances and the forms of substance used in a chemical process should be choosen to minimize the potential for chemical accidents, including releases, explosions, and fires.**

    This principle requires to reduce the use of such substances in chemical processes that can cause adverse effects (explosion, fire and harmful vapor). Accidents, fire and explosions should be avoided as far as possible. In organic chemistry labs, since solvents find so much of use, it is believed that these vocs can be highly flammable and cause fires. It is to be kept in mind that while doing chemistry, incidents like Bhopal gas tragedy should not happen.

3. Planning a green synthesis

To carry out a green chemical synthesis in a lab, following things are to be considered:

1. Choice of starting material.
2. Choice of solvents/appropriate solvent selection.
3. Choice of reagents
4. Choice of catalysts.

5. Choice of energy sources

1. Choice of starting material

Once one intends to design a green chemical synthesis in a lab, the starting material required for that very synthesis should of course be from a renewable source. Most of the chemical synthesis generally use petrochemicals as starting materials. Owing to non-renewable nature, besides requiring considerable amount of energy, it is envisaged to reduce the use of such chemicals, by replacing their use with the starting materials of biological origin. As far as possible, an ideal feedstock (raw-material) should be

a. Renewable
b. Having zero toxicity
c. Converted in to products in a very few steps
d. 100 % atom economy
e. 100 % yielding

e.g agricultural products like corn, potatoes, soya, and molasses are transformed through a variety of processes in to products like nylon, textiles etc. Materials like butadiene, pentane, pentene, benzene, toluene, xylene, phenolics, aldehydes, mannitol, have been obtained from materials of biological origin, molasses.

2. Choice of solvents (Alternative solvents):-

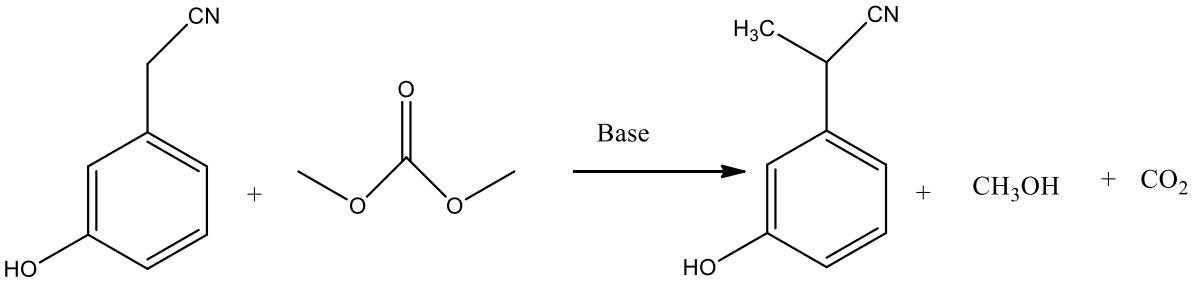
The solvent used for a particular reaction should not cause any environmental or health hazard. e.g. All organic solvents (VOC's) are said to be associated with ill effect on human health . The halogenated solvents like CH_2Cl_2, $CHCl_3$, CCl_4, have long been identified as suspected human carcinogens. Owing to the concerns associated with these solvents, alternative solvents have been proposed for use in chemical reactions. Generally the preferred way to carry out a chemical process is to do it without the use of solvent, if possible. One such solvent-less reaction comprises those

reactions, in which the starting material and reagents serve as solvents. Alternatively the reaction can also be performed in molten/solid form. If the use of solvent cannot be avoided, it is envisaged to carry out reactions in water. Other alternate solvents include, ionic liquids have been developed. Besides these organic reactions have been carried out in supercritical carbon dioxide and water, polyethylene glycol and its solution.

3. Choice of Reagents (Appropriate reagents)

Selection of an appropriate reagent for a reaction is done on the basis of efficiency, availability, and its effect on the environment. The selection of a particular reagent verses another reagent for the same transformation can affect the nature of byproducts, yields etc. Examples of green reagents include:

Dimethyl Carbonate: Methylation is usually carried out by uing methyl halides or methyl sulphate. Bieng toxic they are not desirable to be used as methylating agents. However a green method has been reported by Tundo in literature which employs dimethyl carbonate to carry out the methylation process at the active methylene site and does not produce any inorganic alt



Besides this a number of polymer supported reagents have been used. Such polymer supported reagents are easy to recover at the end of reaction and reused and caue no inconvenience in the isolation of products. Some common examples include:-

a) Polymer supported per acids:- They are helpful in epoxidation of alkenes.
b) Poly NBS:- used as benzylic and allylic brominating agent
c) Polymer supported chromic acid:- used in oxidation of alcohols.
d) Polystyrene anhydride:- used in acetylation of aniline.

4. Choice of catalysts

Catalysts are versatile chemical entities that increase the rate of reaction without being changed, However not all catalysts are green. Certain metal catalysts are toxic in nature and cause problems both to the biotic as well as abiotic environment. Different types of catalysts have been used and are regarded as green catalysts. These include:-

a) Acid catalysts:- e.g microencapsulated catalysts are replacing the traditional lewis-acid catalysts. Similarly flourided silica alumina catalyst is used in place of the corrosive Hydrogen fluoride.
b) Basic catalyst:- Basic catalysts like Mgo and γ-alumina are used in alkylating the benzene rings.
c) Oxidation catalysts:-e.g Titanium silicate is used to carry out the hydroxylation of phenol to catechol and resorcinol and quinol.
d) Photocatalysts:- A large number of photoatalysts have been used to carry out the transformations. e.g TiO based photo-catalytic systems.
e) Biocatalysts: These serve as important tools in green chemistry.

Still biocatalysts stand out among all other catalysts because of their specificity in terms of stereochemistry, chemical selectivity. Compared to non-biological catalysts, biocatalysts have a great advantage given the rate of reaction, catalytic specificity, lower cost, etc., but lack of heat

sensitivity and poor stability. Biocatalysts are biodegradable-catalysts, which imply less energy consumption. e.g *daucous carrota* enables the reduction of carbonyl groups like aldehydes, ketones, etc, which is a biocatalytic reduction.

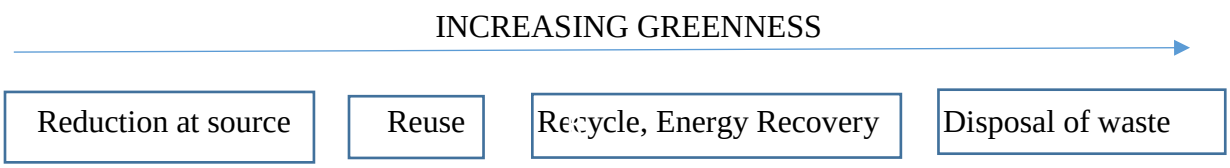
Unit 2

1. Designing a green-process

Same as that of planning a green synthesis in a lab. All the sub-headings like choice of starting material, choice of reagents, choice of solvents and choice of catalysts to remain same in this topic as well

2. Prevention of wastes

Normally a synthesis should be carried out in such a way to prevent formation of wastes. If the waste production cannot be ruled out, it is envisaged to carry out a process which could at least minimize the amount of waste generated. Because once the waste is produced it needs to be disposed of. This leads to overall cost of the process. Further the process should be carried out to ensure 100 percent utilization of the reactants, because any amount of starting material that remains unutilized gets mixed with the products and is regarded as waste. Finally anything that is produced in a laboratory ends as a waste. Because once the product is formed, it is put to use and ultimately is to be discarded and thus ends up as a waste. These wastes can pose any serious problems to the biotic and abiotic environment. To prevent this, the waste minimization, recycling and reuse of wastes is actively employed. Most commonly it is envisaged to reduce the minimization of waste at the source of its production. If however reduction of waste at source cannot be avoided, we should try to reuse or recycle the waste to recover material and or energy. Disposal of waste should be the last choice only. This can be shown below:



3. Maximum incorporation of reactants in to products (Atom economy)

It is one of the fundamental and most important principle of green chemistry. The concept of atom economy has been developed by B.M. Trost. Atom economy is defined as the measure of the amount of reactants that end up directly into the desired product. It is often referred to as percent atom utilization. It gives us the index of how much reactants end up as desired products and how many end up as waste.

R. A. Sheldon has also developed the same concept given as:

$$\%\ Atom\ Economy = \frac{Formula\ weight\ of\ atoms\ utilised\ in\ the\ desired\ products}{Formula\ weight\ of\ reactants\ used\ in\ the\ reaction} \text{ x } 100$$

or

$$\%\ Atom\ Economy = \frac{Relative\ molecular\ mass\ of\ desired\ product}{Relative\ molecular\ mass\ of\ all\ reactants} \text{ x } 100$$

Or

$$\%\ Atom\ Economy = \frac{Molecular\ mass\ of\ desired\ product}{Molecular\ wieght\ of\ all\ the\ products} \text{ x } 100$$

Calculation of atom economy

For a general reaction:

$$A + B \longrightarrow C$$

% Atom economy is given by

$$\%\ Atom\ Economy = \frac{Mass\ of\ Product\ C}{Mass\ of\ reactant\ A + Mass\ of\ reactant\ B} \text{ x } 100$$

Similarly

For a reaction which involves the formation of intermediates and occurs in more than one step, atom economy calculation ignores the intermediates and considers the reactants only. Consider a two step reaction given below

1. A + B $\longrightarrow$ C

2. C + D $\longrightarrow$ E

$$\%\ Ato\ Economy = \frac{Molecular\ weight\ of\ Product\ E}{Molecu\ \ wieght\ of\ reactant\ A + Molecular\ wieght\ of\ B + Molecular\ weight\ of\ D} \text{ x } 100$$

Here in above reaction C has been ignored because it is produced in one step and consumed in next step.

Reactions have been classified as atom economic and atom un-economic reactions. Those reactions in which atoms of all the reactants end in desired products are highly atom economical. In organic chemistry mostly rearrangement reactions, Addition reactions and concerted reaction like diels alder reaction are highly atom economical reactions. While as reactions like substitutions, elimination, Grignard reaction, wittig reactions are treated as atom uneconomical reactions.

4. Minimization of hazardous/toxic products

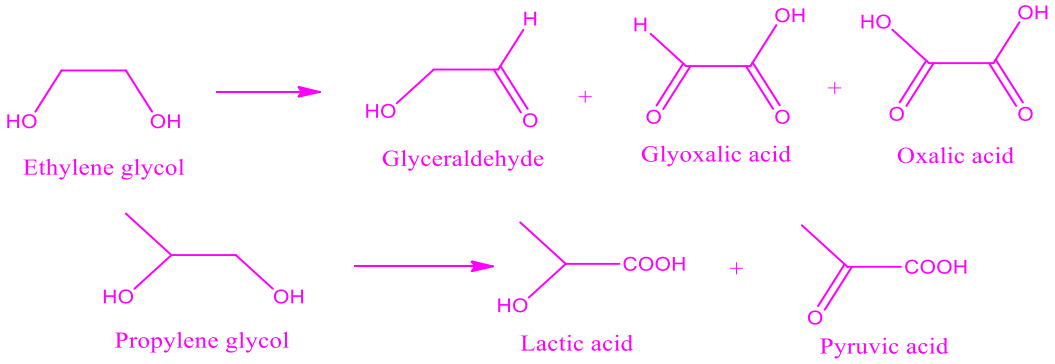
This is one of the important aspects in green chemistry which advocates the minimization of toxic products in processes. A product may be regarded as a hazardous, if it is associated with toxicity, flammability, has explosion problems and gets accumulated with in the environment. The impact of hazardous products should be minimized on the workers by use of protective clothing, googles, respirators. The risk of hazard can be reduced on the workers working in factories producing such chemicals, by just reducing the time of exposure. The harm being caused by the exposure is given as:

Risk = (function) Hazard x Exposure

From the above relation it is clear that to reduce the risk, we need to reduce either hazard or exposure or both. The reduction of hazard is regarded as a green chemical approach to minimize the risk. However if only the time limit of exposure is reduced, it means although little a harm can occur once exposed. If however no exposure is there, it completely eliminates the risk of the hazard.

5. Designing safer chemicals:

Chemical products to be synthesized should be safe to use. Thalidoimide presents an example of a typically unsafe drug, used for reducing the nausea and vomiting in pregnant women. The children born to such women suffered birth defects, which necessatiated the ban on the use of this drug. Manipulation of molecular structures has helped in lot in the design of safer chemicals. A well-known example of retrometabolic design is that of ethylene glycol, which is used as an antifreeze and has been replaced by propylene glycol which is less hazardous. Ethylene glycol once ingested in to body gets converted in to glyceraldehyde, glyoxylic acid and oxalic acid which are toxic to body, as against propylene glycol which gets metabolized into normal body metabolites like lactic and pyruvic acid. The lethal dose of ethylene glycol for man is 1.4 ml/kg while as the lethal dose of propylene glycol for man is 7 ml/kg. Thus propylene glycol is a comparatively safer chemical than ethylene glycol



6. Selection of appropriate solvents: (Green solvents)

Chemists generally use any organic solvent of their choice in synthetic reactions. Most often these solvents are the volatile organic solvents (VOCs) and have a major environmental concern, as they are able to form low-level ozone and smog through free-radicals air oxidation processes. They are also highly flammable and cause adverse effects like eye-irritation, headaches and allergic skin reactions in human biengs. These facts have made it necessary to use green alternative solvents. However if possible the use of solvents should be avoided. If however there is no choice and use of solvent becomes imperative, it is recommended to use such solvents which are inert, have low toxicity, easy to recycle without contaminating the products. The solvent selected should not have any negative impact on the environment or human health. e.g. halogenated solvents like $CHCl_3$, CCl_4 are suspected carcinogens and to avoid their use, green alternatives like water, ionic liquids, liquid CO_2 have been used. To avoid the problems associated with the conventional VOCs, immobilized solvents have been harnessed. Such solvents maintain the solvency, are non-volatile and do not pose any environmental problem.

1. H_2O as Green Solvent:

Water is regarded as the best solvent for the reactions to be carried out. Water however has a number of advantages but at the same time so many disadvantages as well. Water is naturally occurring, non-toxic, non-explosive solvent as against the voc's. However at the same time water is difficult to heat or cool rapidly, its distillation is energy expensive, the contaminated waste streams are difficult to treat.

Although chemical reactions in human systems occurs within the water, but in lab synthetic reactions hardly occur in it. However at higher temperatures the density decreases while the ionic

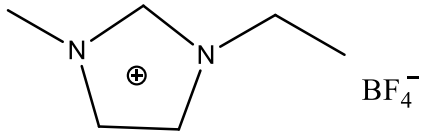
product of water increases. At temperatures of more than 200 ^{0}C water becomes as good as an organic solvent. It is believed that water behaves like acetone at a temperature of 300 °C. This is possibly because higher temperature removes hydrogen bonding in the water. In some reactions a significant amount of rate enhancement has been observed when the reaction is carried out using water. A typical example of this is the Diel's alder reaction between cyclopentadiene and butanone. It has been found that this reaction occurs 700 times faster in water compared to the isooctane.

2. Ionic Liquids

An ionic liquid comprises of a large nitrogen containing organic cation and a small inorganic anion. Since one part is large and other is small, it creates asymmetry in the compound which makes it a low melting solid. Simple ionic liquids when mixed with the other inorganic salts result in the production of a multicomponent ionic liquid. Since the components of an ionic liquid are held by strong forces of attraction, it is found that they possess no or low vapour pressure rendering them non-volatile in nature. Further they are non-flammable and non-explosive which is an additional feature rendering them safe to use. They can also be used both as solvent as well as catalysts. Thus the properties of ionic liquids which make them ideal green solvents include:

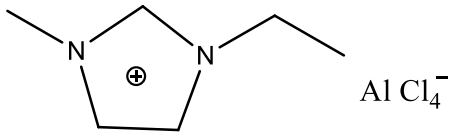
a) Lack of vapour pressure.
b) Non flammability and non-explosiveness.
c) Stable at high temperature which makes them better for carrying out reactions at high temperatures.
d) The property of these ionic liquids can be changed by just changing their concentrations of cations/anions, varying the side chain length in cations.

Few of the ionic liquids are mentioned below:



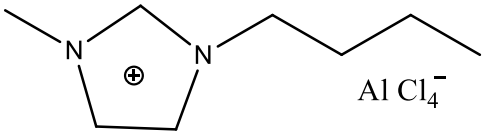
1-ethyl-3-methylimidazolium fluoride-boron (III) triflouride

([bmim] BF_4)



1-ethyl-3-Methylimidazolium chloride-aluminium (III) chloride

([emim]$AlCl_4$)



1-butyl-3-methylimidazolium chloride-aluminium (III) chloride

([bmim]$AlCl_4$)

List of Laboratory exercises with detailed procedures for 5th Sem in Green Chemistry

Syllabus

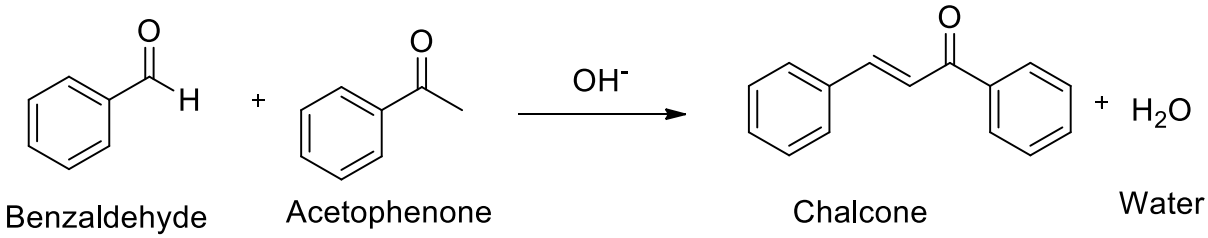
1. **Greener approaches to synthesis (02 Experiments)**
2. **Photoreduction of benzophenone to benzopinacol in sunlight (Photochemical).**
3. **Reduction of acetophenone using Daucus carota root (Enzymatic reaction).**
4. **Micelle assisted reduction of aromatic carbonyl compounds (any aldehyde, ketone or ester) in water using sodium borohydride- A green approach (Aqueous Phase Reaction)**
5. **Aldol condensation reaction in solid phase (Solid-phase reactions).**

Experiment 1 (a): Synthesis of Chalcone from benzaldehyde and Ketone (Acetophenone)

Chemicals Required:

Benzaldehyde	2.2 ml
Acetophenone	2.5 ml
Rectified Spirit	7.0 ml
Sodium Hydroxide	10 % NaOH

Reaction Involved



Procedure:

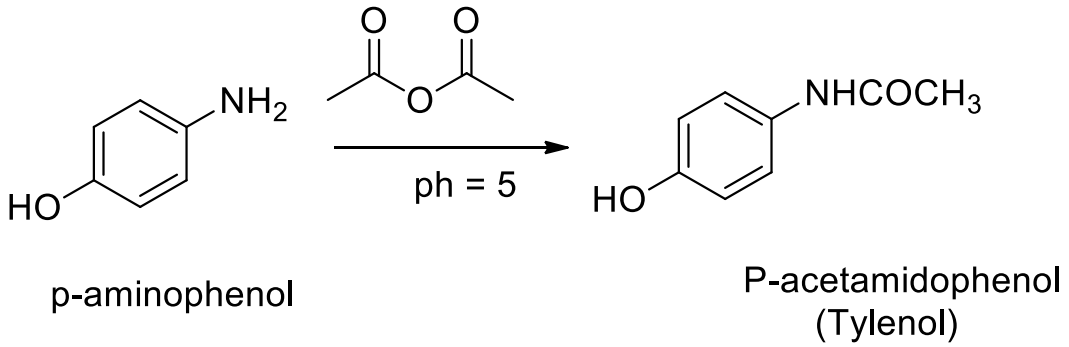
1. Take benzaldehyde (2.2 ml) in a conical flask (100 ml).
2. Add acetophenone (2.5 ml) and rectified spirit (7 ml). Stir the mixture, so as to obtain a homogenous solution. If necessary, the mixture may be warmed to get a clear solution.
3. To the clear solution, add 10 percent freshly prepared NaOH solution and stir. Keep the mixture over night in the refrigerator.
4. Filter the separated chalcone, wash with cold water and recrystallize from alcohol. Calculate the yield and the melting point of the product (which is 56-57 ˚C).

Experiment 1(b): Synthesis of p-acetamidophenol from p-aminophenol

Chemicals required:

p-Aminophenol	2. g
Acetic anhydride	2 ml
Conc. HCl	1.8 ml
Sodium acetate (anhydrous)	2 g

Reaction Involved:



Procedure

1. In a conical flask, take p-aminophenol (2 g) in water (20 ml) containing conc. HCl (1.8 ml) and add acetic anhydride (2 ml) to it.
2. Shake the mixture so that the contents dissolve well..
3. Add a solution of anhydrous containing 2 g of sodium acetate dissolved in 10 ml water.
4. Keep stirring the solution and leave it to stand overnight.
5. Cool the solution in an ice bath.
6. Filter the solution. Crystallize the product. Report the yield and melting point (169 ˚C).

Experiment 1(c): Synthesis of vanillidineacetone from vanillin and acetone

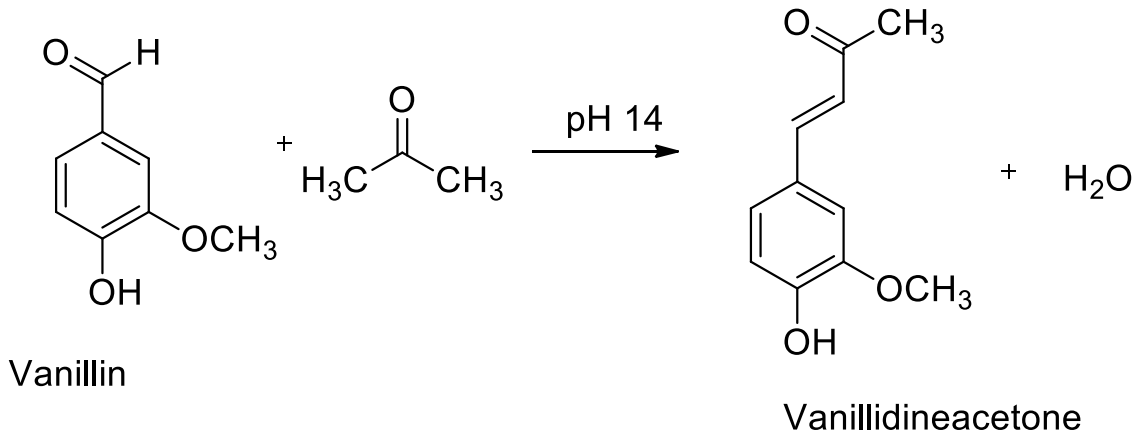
Chemicals Required

Vanillin 2.0 g

Acetone 8 ml

Sodium Hydroxide (6 ml of 10 % solution)

Reaction Involved:



Vanillin

Vanillidineacetone

Procedure

1. Take about 2 g vanillin in a 100 ml conical flask.
2. To this conical flask add about 8 ml of acetone.
3. Add about 6 ml of freshly prepared 10 % solution of NaOH to the content in the conical flask.
4. The reaction mixture is left for 3 days with occassional shaking.
5. Add water (50 ml) while stirring vigorously.
6. Add about 10 ml of 10 % HCl solution
7. Filter the product formed, wash with water and dry it completely.
8. Recrystallize the product using 1:1 ethanol:water (10-12 ml).
9. Report the experimental yield, percent yield and record its m.p.
10. Report your results on your practical manual

Experiment 2. Photoreduction of Benzophenone to Benzopinacol in Sunlight

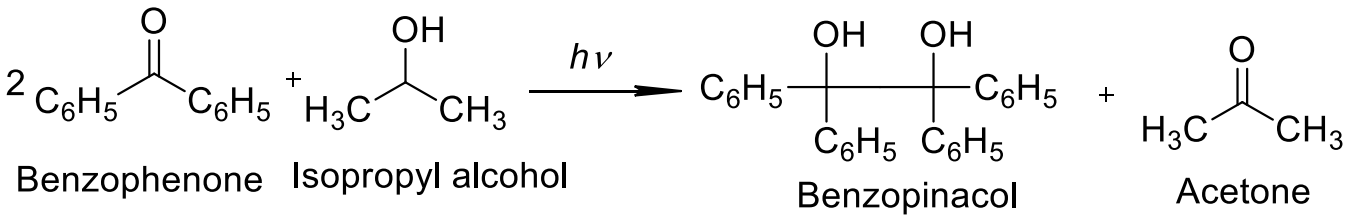
Chemicals Required:

Benzophenone (10.9 g)

Isopropyl alcohol (50 ml)

Acetic acid (1 ml)

Reaction Involved:



Procedure:

1. Take about 10 g of benzophenone in a flat bottomed flask.
2. Add about 50 ml isopropyl alcohol to it.
3. Add glacial acetic acid (1 ml) and add the flask with more isopropyl alcohol.
4. Stopper the flask tightly and place the flask in bright sunlight for about 1 week.
5. Once the product gets separated it is filtered and washed with cold isopropyl alcohol.
6. The product formed is dried. Percent yield is calculated and the melting point which is about 173-177 °C is reported.

Experiment 3: Reduction of Acetophenone using *Daucus Carota* root

Materials/Chemicals required:

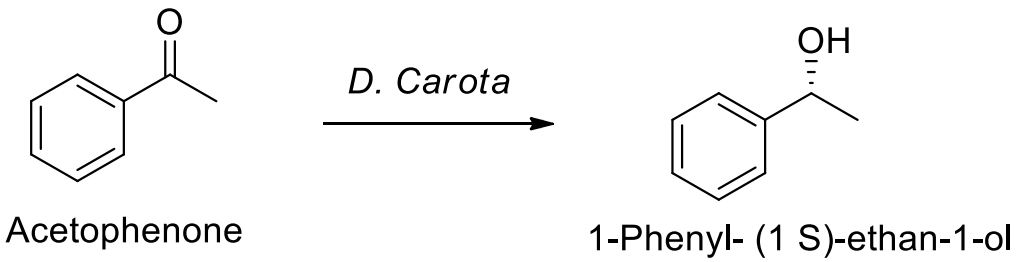
Acetophenone: 2 ml

Slices of carrot: 15 g

Ether: 200 ml

Petroleum ether: 400 ml

Reaction Involved:



Procedure

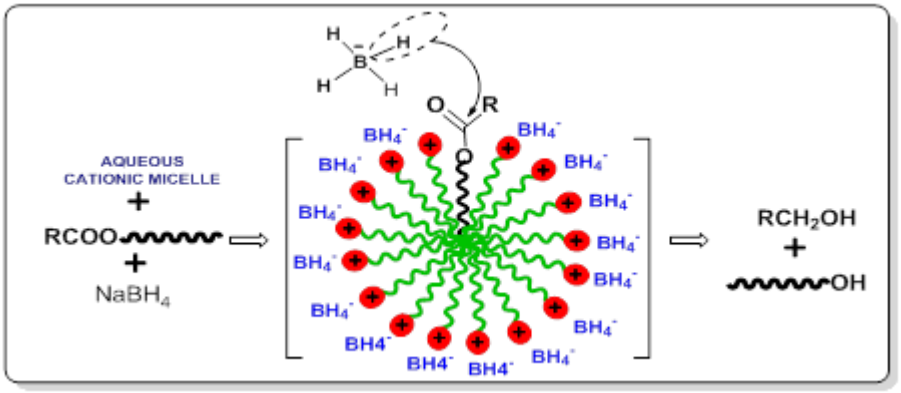
1. Remove the external layer of carrot and then cut it in to small thin pieces (approximately 1 cm long slice).
2. Take 2 ml of acetophenone in about 20 ml water in a flask
3. Add about 15 g of sliced carrots to the flask (10 g).
4. Stirr the reation mixture.
5. The reaction takes about 3 days for completion.
6. Using column chromatography purify the reaction mixture.
7. Elution can be done using ether-petroleum ether (1:2).
8. Report the specific rotation $[\alpha_D]^{25}$ of the product.

Experiment 4: Micelle assisted reduction of aromatic carbonyl compounds (any aldehyde, ketone or ester) in water using sodium borohydride- A green approach

Theory:

In order to reduce environmental toxicity Green approaches are being preferred in the areas of synthesis. Efforts are being made to reduce the use of toxic organic solvents and shift to more environmentally benign solvents like water and some possible strategies include solvent free conditions and mechanochemistry. Among all possible liquids, water is certainly the one with the smallest impact on the environment. Water as a solvent has been selected by Nature to carry out all kinds of chemical transformations no matter whether substrates are soluble or insoluble. Water as a solvent is extremely economical, non-toxic, non-flammable. It does not contribute to greenhouse emissions, does not require synthesis, the energy necessary for its isolation in the pure form is low and its E factor value equals to zero, large heat capacity and heat of evaporation allowing easy control of exothermic reactions, high polarity, and the coexistence of hydrogen bond donor and acceptor functionalities that often make catalysis easier.

Sodium borohydride ($NaBH_4$) reduction of carbonyl compounds is usually done in methanol under anhydrous conditions. The $NaBH_4$ reduction does not occur in pure aqueous medium. However, the reaction can be made to happen in water using micelles (preferably cationic). Interestingly, self-organized aggregates such as aqueous micellar media can bind the otherwise insoluble organic substrates by incorporating their hydrophobic part in the micellar interior and exposing their polar part at the water micelle interface. Moreover, they offer a clean and viable alternative to traditional methods of accomplishing organic transformations. The intrinsic solubilization ability of micelles provides a discrete reaction site at the microheterogeneous interface by bringing the reacting molecules in close proximity. Hence, the local interfacial concentrations of reactants get enhanced compared to their stoichiometric concentration. The energy of activation is lowered presumably due to increased collisions between such interfacially concentrated reactants.



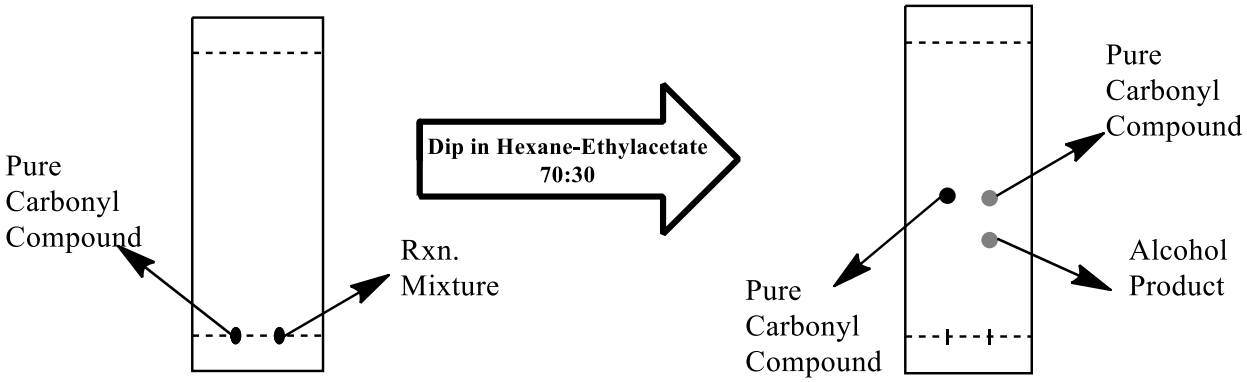
Schematic representation of micelle assisted reduction of an ester in water.

Requirements:

1. An aromatic carbonyl compound (50 mg).
2. Cationic surfactant cetyltrimethylammonium bromide, CTAB (10 mM) or use any other cationic surfactant (concentration should be about ten times CMC).
3. TLC plate and spotting capillaries.
4. A glass vial and magnetic bead.
5. Magnetic Stirrer

Procedure:

1. Take about 10 mL of 10 mM CTAB solution in a vial containing magnetic bead.
2. Add 20 mg of carbonyl compound to the vial.
3. After about 20 mins, add 30 mg of $NaBH_4$ and stir for about half an hour.
4. Follow the reaction using TLC. Using capillary do appropriate separate spotting (of reaction mixture and parent carbonyl) on TLC plate after every 10 min. Dip the TLC plate in mobile phase (Hexane and Ethylacetate in 70:30 ratio).
5. Visualize the developed TLC in UV chamber or dip the TLC in Chromic acid and heat till spots appear.
6. An additional spot below pure carbonyl will appear on TLC and with time it will grow and that of carbonyl will vanish. This marks reaction completion.


Pure
Carbonyl
Compound
Rxn.
Mixture
Dip in Hexane-Ethylacetate
70:30
Pure
Carbonyl
Compound
Alcohol
Product
Pure
Carbonyl
Compound

Experiment 5: Aldol condensation reaction in solid phase

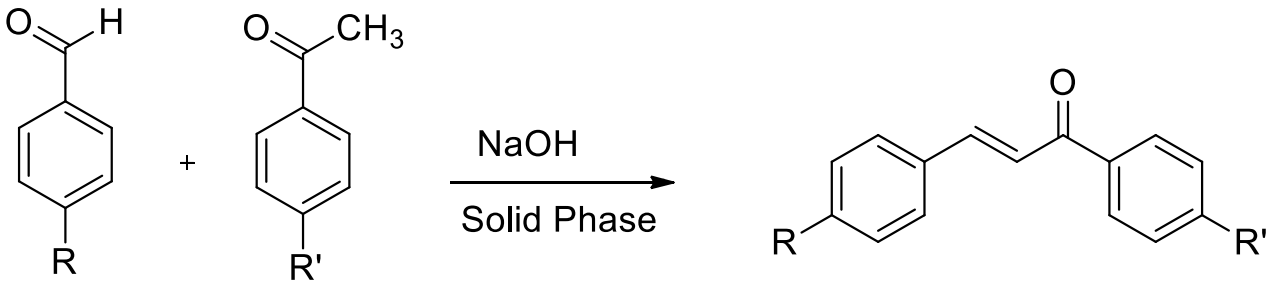
Chemials Required:

Aromatic Aldehyde: 1 g

Substituted Acetophenone: 1 g

NaOH: 0.20 g and HCl: 10 % solution

Reaction Involved:



R can be
Cl or OMe
or CH_3

R' can be
Me or OMe

Procedure

1. Grind 1 g of p-methoxybenzaldehyde (or p-chlorobenzaldehyde or p-methylbenzaldehyde) and 1 g of acetophenone (or p-methoxyacetophenone or p-methyl acetophenone) separately in a pestle and mortar.
2. Mix the two and crush further to allow mixing of both solids
3. Add 0.20 g of finely divided NaOH to the reaction mixture.
4. Allow the mixture to stand for some time.
5. Then add about 10 ml of 10 % aqueous HCl solution.
6. Ensure the solution is acidic, filter, wash with 1 ml of water and dry the compound. Carry out the recrystallization from ethanol.